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IN A PLASMA - APPLIED TO PLASMA DIAGNOSIS

by

Zhong Quande

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COALESCENT FOUR WAVE FREQUENCY MIXING IN A PLASMA

—— APPLIED TO PLASMA DIAGNOSIS

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The so-called coalescent four wave frequency mixing means the phenomenon of producing a signal wave of same frequency (the 4th beam) which is colinear with the probing wave, but opposite in propagation direction and conjugate in phase by frequency mixing in a medium with 3rd order polarizability, 2 laser beams (first and second beam) of same frequency, colinear and propagating in opposite directions with another probe light beam (the 3rd beam) with the same frequency but arbitrary direction. As shown in Figure 1, the practical value of coalescent four wave frequency mixing in real-time signal potential processing and phase difference compensation induces broad research in various types of media such as solids, liquids, crystals, metallic vapors and dyes by many researchers [1-8]. /156

Recently, Steel, Lam and the author [10] calculated for the first time the 3rd order non-linear polarization of coalescence and double coalescence in a plasma and pointed out that the plasma is a good non linear medium for coalescent 4 wave frequency mixing in the whole range from infra-red to microwave. The author [10] has the opinion that the coalescent four wave frequency mixing technique is very suitable for plasma diagnostics. It is easy to obtain a signal power much bigger than that of non-coherent Thomson scattering. Since coalescent four wave frequency

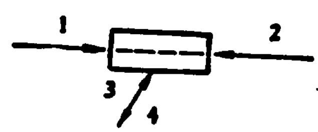

Figure 1. Diagram of four wave frequency mixing.

mixing can automatically satisfy the condition of phase matching and requires no attached excitation devices, it is much superior to the ordinary coherent scattering diagnostic [1-14] (e.g., ion accoustic scattering diagnostics).

The signal wave produced by coalescent four wave frequency mixing (the 4th wave) comes from the 3rd order polarization intensity triggered by the joint action of the 1,2, 3rd beams on the medium. For a plasma, it results from the 3rd order non-linear macrocurrent

$$J = \sum_j n_j \cdot q_j \cdot V_j,$$

where j represents the various types of particles in the plasma, q_j the electric charge on the particle, n_j the particle density and V_j the drift velocity driven by the external field. The Plasma density fluctuation is induced by the non-linear Lorentz force $V_j \times B/c$ and the convection term $V_j \cdot \nabla V_j$. Let the 3 laser beams incident on the plasma with the same frequency to be

$$E_n(r, t) = E_{n0} \cos(\omega t - K_n \cdot r), \quad n = 1, 2, 3. \qquad (1)$$

Here, the 1st and 2nd beams are assumed to be non-decaying plane waves. They are colinear, but propagating in opposite directions, hence $K_1 + K_2 = 0$. The 3rd beam is incident from some arbitrary direction. We shall assume that the initial state of the hydrogen plasma is uniform, thermal, non-magnetised, and not dense, i.e., $\omega \gg \omega_{pe}$. (electron plasma frequency). According to the dynamics describing this plasma in an external field by the 2-fluid theory, the method of solution is the standard stepwise approximation method, as adopted in references [15] and [16]. It is to be pointed out here that for small perturbation theory, the small parameters are $v_1/c \sim eE_{0n}/m\omega c \ll 1$. Thus, the electron density fluctuations induced by the mass dynamic caused by the combined effects of beams 1 and 3 or beams 2 and 3 is

$$n^{(2)} = \sum_{n=1}^{2} \tilde{n}_{0n} \cos[(K_n - K_3) \cdot r],$$

$$\tilde{n}_{0n} = -(N_0 r_0 \lambda_0 E_{0n} \cdot E_{03}^{*}) \Big/ \Big\{ 6(2\pi)^2 k_B T_e \times \Big[1 + \frac{1}{3\lambda_{De}^2 (K_n - K_3)^2} \times \Big(1 - \frac{1}{3\lambda_{Di}^2 (K_n - K_3)^2 + 1} \Big) \Big] \Big\}, \tag{2}$$

where r_o is the classical electron radius, λ_c the laser wavelength, /157
No, Te, λ_{D_e} and λ_{D_i} respectively the plasma electron density, electron temperature, electronic and ionic Debye lengths, k_B the Boltzmann constant. The 3rd order polarizability P_4 of frequency W produced jointly with the drift velocity V_j driven by the external field is

$$\begin{aligned} P_4 = 3\mathrm{Re}[& \chi_{13}^{(3)}(E_{\omega} \cdot E_{\omega}^{*})E_{\omega} \\ & + \chi_{23}^{(3)}(E_{\omega} \cdot E_{\omega}^{*})E_{\omega 1}] \\ & \times \exp i(\omega t + K_s \cdot r), \end{aligned} \quad (3)$$

Here the 3rd order polarization $\chi_{\omega}^{(3)}$ is

$$\begin{aligned} \chi_{\omega}^{(3)} = -[N_0/N_c^2(\omega)] \Big/ \Big\{ & 3(4\pi)^2 k_B T_e \\ & \times \Big[1 + \frac{1}{3\lambda_{De}^2 (K_e - K_s)^2} \\ & \times \Big(1 - \frac{1}{3\lambda_{Di}^2 (K_e - K_s)^2 + 1} \Big) \Big] \Big\}, \end{aligned} \quad (4)$$

where $N_c(\omega)$ is the critical cut-off density of the electromagnetic wave. When $\lambda_{Di}(K_e - K_s) \ll 1$, the above formula simplies to

$$\chi_{\omega}^{(3)} = -\frac{N_0/N_c^2(\omega)}{3(4\pi)^2 k_B (T_e + T_i)}; \quad (5) \qquad (5)$$

and when $\lambda_{De}(K_e - K_s) \gg 1$ to

$$\chi_{\omega}^{(3)} = -\frac{N_0/N_c^2(\omega)}{3(4\pi)^2 k_B T_e}, \quad (6) \qquad (6)$$

With the exception that the exponent of the 3rd order polarizability corresponding to the probing wave takes the form of $\exp i(\omega t - K_s \cdot r)$; it has a similar form as eq. (3). It is precisely the electric moment represented by the polarizability in eq. (3) that radiates the signal wave conjugate in phase to the probing wave. Solving the wave equation according to the non-linear optical method, we then obtain the ratio of the signal power to probing wave power, i.e. the reflective

coefficient R as

$$R = \frac{P_4}{P_3} = \mathrm{tg}^2(\omega|\kappa|L), \qquad (7)$$

where the complex K Coefficient is

$$\kappa^* = \frac{3\pi}{c}\sum_{n=1}^{3} \chi_{n3}^{(3)} E_{n} E_{n}, \qquad (8)$$

L being the interaction length.

The coalescent four wave frequency mixing mechanism in a plasma may also be considered as the 2 spatial electron density gratings in Equation 2 caused by the 1st and 3rd beams or the 2nd and 3rd beams in the plasma, which produce the 4th beam by Bragg reflection, respectively, on the 2nd beam and the 1st beam. The reflected optical energy concentrate in the direction K_3 while the energy of non-coherent Thomson scattering is uniformly distributed in a solid angle of 2π steradian.

From Equation (2) and (3) we can also obtain the polarization selectivity in a plasma of the coalescent four wave frequency mixing as shown in Figure 2. If the polarization direction of the 3rd beam is the same as that of the 1st beam (or the 2nd beam), then the polarization direction of the signal wave will be the same as that of the 2nd beam (or 1st beam). Otherwise, the coalescent four wave frequency mixing effect will be weakened or will fail to occur. This polarization characteristic is very important to plasma diagnostics. For example, if the angle between beam 1 and beam 3 satisfies

$$\lambda_{D1}(K_1 - K_3) \ll 1$$

then, even if Equation (5) holds, the angle between beam 2 and beam 3 will make $\lambda_{Dm}(K_3 - K_4) \gg 1$, i.e., Equation (6) will hold. Making use of the polarization selectivity as mentioned above, distinguishing between the signals produced under these two circumstances; hence, the coalescent four wave frequency mixing technique, may become a

new way to diagnose the electronic and ionic temperatures of a plasma.

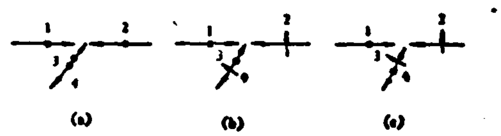

Figure 2. The polarization relations of beams in a plasma.

In order to compare easily with other scattering diagnostics, we substitute Equation (4) into Equation (7). Under a small power approximation, the signal power [when $\lambda_{De}(K_e - K_s) \gg 1$] of the coalescent four wave frequency mixing becomes after some algebra

$$P_4 = \left(\frac{4N_0}{N_c(\omega)}\right)^2 \cdot \frac{1}{(k_B T_e)^2} \cdot r_0^2 \lambda_0^2 L^2 \cdot \frac{P_1 P_2}{S^2 c^2} \cdot P_3, \qquad (9)$$

where S is the beam cross-section. The signal power is proportional to the electron density, which is precisely what is predicted by coherent scattering. The signal power is also inversely proportional to the electronic temperature and directly proportional to laser wavelength. We know that the scattering cross-section of the non-coherent Thomson scattering in the solid angle $\Delta\Omega$ at 90° for a laser in a plasma is $1/2\ r_0^2 N_e$; if the scattered light is separated into channels with a spectrograph, then the scattering power into each channel is

$$P_T = \frac{1}{2\beta} N_e r_0^2 L \Delta\Omega P_0.$$

Hence, we obtain the ratio of the coalescent four frequency mixing signal power in a plasma to the 90° Thomson scattering power to be

$$\frac{P_4}{P_T} = 32\left(\frac{N_0}{N_c^2(\omega)}\right) \cdot \frac{1}{(k_B T_e)^2} \cdot \frac{\frac{\lambda_0^2 L \beta}{\Delta\Omega} \cdot \frac{P_1 P_2}{S^2 c^2}}{6}, \qquad (10)$$

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Apparently, this ratio is very large. For example, the plasma parameters are

$$N_0 = 5 \times 10^{13}\mathrm{cm}^{-3}, \quad T_e = 100\mathrm{eV},$$

When we choose a methane fluoride laser with $\lambda_0 = 496\mu\mathrm{m}$, laser cross-section diameter $\phi 2\mathrm{mm}, L = 1\mathrm{cm}$, laser power $\sim 10\mathrm{kW}$, then the signal power for coalescent four wave frequency mixing obtained is 10^3 times the scattering power of 90° Thomson scattering with the same laser power. (When $\Delta\Omega \sim 3 \times 10^{-4}, \beta = 10$). Thus, when the temperature of the plasma is not too high, choosing the laser wavelength suitably, it is possible to obtain the signal power for the coalescent four wave frequency mixing $\sim 10^{-14}\mathrm{W}$ with a laser power of a few dozen milli-watt. This demonstrates clearly that it is possible to use continuous infra-red lasers of relatively low power as the source for frequency mixing in a continuous wave diagnosis of a plasma.

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